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NAVORD REPORT 3890

EXPLOSIONS IN ENCLOSED SPACES II:

MEASUREMENTS AND THEORY ON "STATIC" PRESSURE FROM HIGH EXPLOSIVES DETONATED IN AIR AND NITROGEN ATMOSPHERES

FC

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EXPLOSIONS IN ENCLOSED SPACES II: MEASUREMENTS AND THEORY ON "STATIC" PRESSURE FROM HIGH EXPLOSIVES DETONATED IN AIR AND NITROGEN ATMOSPHERES

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ABSTRACT: This report describes measurements on relatively long duration pressures generated when high explosives are detonated in a completely closed space and presents a quantitative description of internal blast phenomena.

Two ounce charges were fired in a 72.4 cubic foot closed chamber in air and nitrogen. The explosives were pentolite, RDX, and RDX/Al compositions containing 22, 35, 50 and 70 per cent aluminum. Characteristic pressure-time curves of the gas pressure in the chamber were obtained using an inductance gage-FM system as well as a piezoelectric gage system with photo-oscillographic recording on drum cameras.

When charges were fired the usual short duration shock wave was observed along with its many reflections which persisted for about 100 milliseconds; however, these shock characteristics were found to overlay a general pressure rise ("static" pressure) which decayed to one fourth of its maximum value in about 500 milliseconds. The characteristic shape of the static pressure obtained from composite curves for each explosive showed a pressure rise to a peak within a few milliseconds, a drop off rapidly for 50 to 100 milliseconds, and a slower drop thereafter. The slow decay rate was found to be definable in terms of convection and conduction of heat across the boundary between the gas and steel chamber wall. Maximum pressure, Δp, was determined by extrapolating this thermal decay back to zero time.

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This work is part of a continuing program under Task NOL-M2c-53-1 of the Bureau of Ordnance. The first NAVORD Report 2984 covered preliminary efforts. This report describes work which has made possible a general quantitative description of the characteristic feature of enclosed space blast, referred to here as the "static" pressure rise. The nature of the interaction of ambient oxygen with exploding material in a closed chamber has also been clarified.

The author is indebted to Dr. D. Price for her encouragement and suggestions. The great assistance of William Clark during the firing program is especially appreciated.

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By direction

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SYMBOLS

A - Chamber surface area

c - Velocity of sound

c_p - Specific heat at constant pressure

c_v - Specific heat at constant volume

$\gamma = \frac{c_p}{c_v}$ - Ratio of the specific heats (1.4 for N_2 and Air)

h - Heat release per gram of explosive

H - Heat release of explosive charge

K - Boundary heat conduction constant of chamber walls

L - Length of chamber

$\lambda = \frac{r}{W^{1/3}}$ - Reduced distance

m - Mass of gas

P - Absolute ambient pressure before explosion

P_a - Absolute ambient pressure after explosion

$\Delta P = P_a - P$ "Static" pressure rise above initial pressure

ΔP_{max} - Maximum "static" pressure rise (measured ΔP)

Q - Rate of heat conduction across chamber boundary

r - Radial distance from a charge

R - Gas constant on a gram basis

ρ - Density of gas in chamber

T - Initial absolute temperature of gas in chamber

ΔT - Rise in temperature of gas corresponding to "static" pressure rise

τ - Period of chamber cavity resonance

W - Weight of explosive

V - Volume of chamber

EXPLOSIONS IN ENCLOSED SPACES II: MEASUREMENTS AND THEORY ON "STATIC" PRESSURE FROM HIGH EXPLOSIVES DETONATED IN AIR AND NITROGEN ATMOSPHERES

INTRODUCTION

A large portion of military targets are structures which more or less completely enclose a volume of air — buildings, airplanes, ships, etc. Damage by external blast on these structures has been extensively explored experimentally and theoretically. It was only late in World War II that systematic investigations of the effects of high explosives detonated in enclosed spaces was undertaken by W. E. Gordon at the Underwater Explosives Research Laboratory (references 1 and 2), although it was known before that internal explosions do much more damage to a given target for the same weight of explosive than a near miss on the outside.

In recent years much work has been done at the Ballistics Research Laboratory and the National Fireworks Ordnance Company on damage to targets from internal explosions using direct damage tests. These empirical experiments have suffered in damage interpretation from the lack of knowledge regarding the basic phenomena involved. The work at NOL is directed at providing some of this information.

The work by Gordon is of special interest because of its fundamental approach and the scope of the measurements. The experiments by Gordon were designed to determine the relative merit of several explosives detonated in a nearly closed (vented) chamber. The size of the charges and the size of the opening in the chamber were systematically varied. Pressure as a function of time was recorded for several hundred milliseconds using piezoelectric gages of the general type employed in air blast shock measurements. He observed not only the expected shock wave and the many reflections from the chamber surfaces but found that these were superposed on a relatively uniform pressure rise in the chamber. It was found that this "static" pressure eventually dropped to atmospheric pressure in a time of the order of hundreds of milliseconds. By varying the size of the opening in the chamber wall the time for the "static" pressure to decay to zero could be varied. Varying the type of explosive varied the level of the "static" pressure rise in direct proportion to the heat of combustion of the material used.

Borrowing from a theoretical treatment by Jones (reference 3) for dust explosions of combustible material in a room with an opening, Gordon proposed to explain the "static" pressure rise in terms of rapid heating of the air in the chamber by the heat liberated from complete-rapid combustion of the explosive using the oxygen of the air in the enclosure to supplement that in the explosive. Quantitative agreement of experimental measurements with this theory was found to be unsatisfactory.

In practical military situations vents of some sort are likely to exist; they may be openings originally part of the structure, or they may result from the blast effects themselves such as fragments, the shock wave, and the "static" pressure rise. However, the experiments at the Naval Ordnance Laboratory (NOL) have been conducted in a completely closed chamber since it is felt that venting problems may be dealt with best after the completely closed situation is understood

THEORY AND PHYSICAL PRINCIPLES

Essentially, the chamber may be treated as a calorimeter. The heat released by the explosive raises the temperature of the ambient gas in the chamber. By measuring the temperature rise, ΔT, of the mass, m, of the gas in the enclosure the heat, H, released by the reaction may be determined from the relation,

$$H = c_v m \Delta T; \qquad (1)$$

where c_v is the specific heat at constant volume of the gas. This equation assumes that the quantity of reaction product gases are negligibly small so that c_v and m in equation (1) refer only to the ambient gas. Since thermal conduction will cause the temperature to drop rapidly, and since transient temperature measurements are difficult to make, the temperature rise may be determined from the measured pressure rise, ΔP, using the gas law for constant volume,

$$\frac{\Delta T}{T} = \frac{\Delta P}{P}; \qquad (2)$$

where T and P are absolute temperature and absolute pressure of the ambient gas before firing. Substituting equation (2) into equation (1),

$$H = mc_v T \frac{\Delta P}{P} . \qquad (3)$$

Now, $c_p - c_v = R$ or $\frac{c_v}{R} = \frac{1}{\gamma - 1}$; (4)

where c_p is the specific heat at constant pressure,

$\gamma = \frac{c_p}{c_v}$, and R is the universal gas constant.

From the gas law, $\frac{P}{\rho} = RT$ or $\frac{T}{P} = \frac{1}{R\rho}$. (5)

Substituting equations 4 and 5 into equation 3, we have

$$H = \frac{m \Delta P}{\rho(\gamma - 1)} \quad \text{or} \quad \frac{\Delta PV}{\gamma - 1} ; \tag{6}$$

where V is the volume of the chamber.

Equation 6 describes the relationship, for explosions in a fixed volume, between the heat released in the explosion, the pressure rise in the ambient gas and the γ of the ambient gas. When any two of these three variables are known, the third may be calculated. For the present study, interest is in the pressure rise. Equation 6 offers a method of predicting the pressure rise with known values of γ and H. It is interesting to note that these physical principles are the basis for a method of determining γ of gases at high temperatures (reference 4). In this instance H is known and Δ P is measured.

The energy obtained from a high explosive depends on the ambient gas in which it is fired as well as the chemical structure of the explosive. Energy released from a high explosive fired in a vacuum or in an inert gas such as argon or helium is generally calculated by subtracting the heat of formation of the explosive from the sum of the heats of formation of the arbitrary decomposition products in the order $H_2O(g)$, CO and CO_2. To the extent of the oxygen available in the original compound these products are usually assumed to be formed in that order. This heat is generally referred to as the heat of detonation.

If oxygen is present in the atmosphere surrounding the explosive, further oxidation of the carbon to CO_2 occurs. When this goes to completion the total heat released is the heat of combustion. Bomb calorimetry for high explosives uses oxygen under pressure to measure this quantity. In an atmosphere containing oxygen in concentrations, such as are found in air at

sea level, little is known about the speed with which the ambient oxygen is utilized. It is known that in atmospheric air some energy due to ambient oxidation is contributed to the shock wave. This is referred to as afterburning, but little quantitative data on this phenomenon are available (reference 1).

INSTRUMENTATION

Explosive charges were detonated in a cylindrical closed chamber. The resulting pressure was measured using a piezoelectric (PE) gage system and an inductance gage system simultaneously. From the inductance gages oscillogram pressure-time histories of "static" pressure in the chamber were obtained and were smoothed and averaged for the several shots and gages. From the PE gages a high resolution record was obtained simultaneously which gave information on the incident shock.

The Chamber Facility

The chamber (reference 5 and Fig. 1) is a cylinder 6 feet long, 3.92 feet in inside diameter and has an enclosed volume of 72.4 cubic feet. It was designed to withstand pressures generated by the detonation of two ounces of TNT. Since the pressures themselves were under study, the design criteria were somewhat tenuous. However, after something of the order of 80 firings in the past 18 months, no deterioration or deformation has been noticed. The chamber is constructed of 1/2 inch thick steel with 1-1/2 inch thick hinged doors secured by 24 bolts and sealed with a recessed rubber "O" ring. Twenty-two access holes designed with rubber sealing glands are arranged about the cylinder walls to accommodate cables, gages and piping. A Stokes rotary vacuum pump is connected to the chamber.

Inductance Gage System

The inductance gage system satisfies the D. C. response requirements of "static" pressure measurements. It is relatively poor in high frequency response (1000 cps) and does not "see" the individual incident and reflected shocks, thus providing a smoothed record that is convenient to read.

The inductance gage proper is outside of the chamber. Gas pressure from the chamber is led to it through a 1/8-inch by 1-1/2 inch long tube. The pressure actuates a diaphragm.

This varies the inductance of a magnetic element which is part of an oscillator circuit. Thus the oscillator frequency is varied by the pressure being measured. The resultant FM signal is passed through a discriminator and is applied as an amplitude modulated signal to the deflection plates of an oscilloscope. Calibration of this gage is performed statically by means of a dead weight tester. This gage is described under the designation TTP-3 in reference 8.

Piezoelectric Gage System

The piezoelectric gage system used to record the incident shock wave is of a type developed in World War II and is in standard use for air blast pressure-time measurements at this laboratory. The gage and system are essentially those described in references 6 and 7. The piezoelectric material, tourmaline in this case, generates a quantity of charge directly proportional to the pressure applied to it. The charge carried by the capacitance of the input circuit gives rise to a voltage which is amplified and applied to the deflection plates of an oscilloscope. The deflection of the cathode ray spot on the oscilloscope is photographed.

The gage is mounted in a circular baffle 10 inches in diameter to reduce error due to the presence of the gage in the flow behind the shock. Unlike ordinary air blast measurements, however, it is necessary here to mechanically insulate the gage from the baffle by means of rubber in order to prevent spurious oscillations from developing in the gage. The whole unit is rigidly mounted perpendicular to the wall and extends out into the chamber space (Fig. 1).

While the extremely fast response of this type of gage is ideal for shock measurements, the system is handicapped for long duration pressure pulse measurements because of its poor low frequency response characteristics. The error is substantial for recording out to times of interest in "static" pressure measurements. For this reason the piezoelectric gages are used mainly to measure the initially occurring shock pressures which are of short duration. These gages are calibrated by the application of shocks whose amplitudes are known by independent means (shock tube or field velocity calibration).

Recording System

The oscilloscope trace of pressure-time records was photographed by means of drum cameras. For the inductance gages the drum cameras rotated at approximately 180 rev/min. The PE gage data were recorded at two speeds by paralleling the amplifier output of each gage to two oscilloscopes, one being photographed at the same speed as the inductance gage signal, the other at about 500 rev/min. At the high drum speed the initial incident shock wave was clearly resolved.

Five hundred cycle timing marks appear on all records, They originate from a series of decade counters operating off a 100 KC crystal controlled oscillator. The timing signal is applied to the deflection plates of 2-inch oscilloscopes located in the field of view of each of the drum cameras. The camera is so arranged that two signal oscilloscopes and a timing oscilloscope are photographed simultaneously and appear on one film.

EXPERIMENTAL PROCEDURE

Explosive Material

The explosive charges were cylinders 1 inch in diameter with a length to diameter ratio of between 1.5 to 2 depending on the density. They weighed 56.3 $\pm$ 0.5 gms.

Six different explosive compositions were employed in the tests; pentolite (50% TNT + 50% PETN) and a series of mixtures containing RDX, aluminum and wax. The exact compositions were 98/0/2, 76/22/2, 63/35/2, 48/50/2, and 28/70/2. The wax was used to satisfy minimum desensitization requirements. Since pentolite had been used in an earlier program it was repeated as a control. The RDX/aluminum mixtures were tested to determine the maximum amount of aluminum useful in contributing to the "static" pressure rise. RDX was chosen in these tests because it was felt that its high sensitivity would be favorable to proper detonation of the high aluminum content mixtures in the small charge sizes being used.

The aluminum used was in the form of particles of mixed sizes. Two particle size grades - 40 and 100 mesh - were used with no noticeable effect on pressure measurements.

Initiation was accomplished by means of #8 and #6 electrical blasting caps placed in a one-half inch deep hole drilled in one end of the charge. No difference in pressure was noted when the results of the two detonators were compared.

Gage-Charge Geometry

The charge was located on the chamber axis about two feet from the access door; that is, one foot off the mid point of the chamber. Placing the charge one foot from the center of the chamber increased the distance from gage to charge sufficiently to reduce the incident shock pressure reaching the piezoelectric gages to values comparable to free air measurements that have been made. The charge itself was oriented with its cylindrical axis perpendicular to the chamber axis so that the PE gages would "see" a cylindrically symmetrical shock. Distances between charge and PE gages were accurately measured on each shot. Two gages of each type were used. All were located in nearly the same plane about one foot from the end of the chamber (Fig. 1).

Firing Procedure

Three charges of each of the six explosive compositions were fired with normal atmospheric air in the chamber. Three pentolite charges and one of each of the other explosives were fired in a nitrogen atmosphere. Firing proceeded in series containing one of each explosive: Pentolite, RDX, and RDX/Al mixtures in increasing order of aluminum content. Four series in all were fired. On the fourth series two additional pentolite charges were fired. Table I shows the controlled variables in this program. The detonator and aluminum size were, of course, minor variables.

TABLE I

CONTROLLED EXPERIMENTAL VARIABLES

Series	Detonator	Aluminum Mesh Size	Ambient Gas
1	#6	100	Air
2	#8	100	Air
3	#8	40	Air
4	#8	100	N_2

The ambient gas change was accomplished by evacuating the chamber, flushing twice with nitrogen before filling to atmospheric pressure. No special effort was made to make the tank vacuum tight in these tests. The lowest pressure attainable in the tank was 7 mm. From leakage rate observations combined with manufacturers specifications of 0.2% oxygen content in the nitrogen, it was estimated that the chamber contained approximately 25 gms of oxygen or that 95% of the oxygen of the air was removed. Since this quantity of oxygen is still sufficient to have caused substantial oxidation of the explosion products, and since this was not observed, it must be assumed that either the estimate of oxygen content is high or that oxidation could not take place rapidly enough at these low concentrations to be observed by our method of measurement.

EXPERIMENTAL RESULTS AND DISCUSSION

Figure 2 illustrates the records obtained from one shot. In Fig. 2a and 2b we see the incident shock clearly resolved, followed by a series of distinct reflected shocks whose position and amplitude are a function of the chamber geometry. Figure 2c is a record of the same shot from the same gage but using another scope with slow speed recording. The early shocks are still distinguishable. Figure 2d is an inductance gage record. It cannot follow the sharp pressure rises in the shock waves, thus the smoother appearance. A characteristic feature of record 2c and 2d is the low frequency oscillation which has been present on all gages and all shots. Extensive measurements on the period of this oscillation were made in this program.

Inductance Gage Data

The main task of data reduction was to reconstruct a smooth pressure-time curve from the film pressure-time records with a much enlarged pressure axis so that the shape of the pressure-time curve could be studied and the maximum static pressure found. (From our present understanding it should be possible in the future to obtain this in direct recording with proper instrumentation.) This reconstruction of the film records was accomplished with the use of an area integrating device. The area under a portion of the record was measured. Dividing this area by the time axis interval gave the mean amplitude. The resulting data consisted of a series of points representing average pressures for each interval. The interval of measurement was one oscillation period. Readings were made on each record out to 150 to 200 milliseconds as was done on our earlier program. Later analysis of graphical plots of the data revealed the desirability of reading out to the limit of available time of

recording which was 500 to 600 milliseconds. To speed the operation, integrations were made over 50 millisecond intervals for the latter data.

Each individual set of record data was plotted. From these plots pressures were read at fixed intervals, averages taken for all data on each explosive composition and a composite graph for each explosive mixture was plotted. Figure 3 consists of all composite plots for all explosive compositions fired.

Two features common to all of the curves stand out, the slow long-time decay of pressure and the initial apparent overshoot or hump. It was found that the decay rate was proportional to the pressure and temperature level and this led to an interpretation based on the assumption of convection-conduction heat loss to the chamber's wall.

Since the gas is in violent turbulent motion, we assume the temperature of the gas at the wall to be the same as that throughout the chamber, and thus may treat the loss as conduction across a boundary between a gas and steel. The temperature of the steel does not rise significantly for the quantity of heat involved because of its great heat capacity compared with that of a gas. The conduction equation may be written $Q = K_A \Delta T$; (7)

where ΔT is the temperature difference between the gas and the steel, A the surface area of the chamber in square feet, and Q the rate of heat transfer in calories per second. K, then, is a constant characteristic of the complex boundary composed of stagnant air, rust, solid products of explosion, etc., with units of cal/sec deg. ft^2.

Figure 4 is a plot of Q vs ΔT and reasonable linearity is apparent. The values for Q were computed using Fig. 3 and Eq. 6. The heat transfer rate was determined for each curve over the 400 millisecond time interval from the 100 to the 500 millisecond points of Fig. 3. ΔT was computed from Eq. 2 using representative initial values (T = 273 and P = 14.7) and values for ΔP from Fig. 3 read at the 300 millisecond point, the midpoint of the Q interval. Table II includes values for K determined with values from each composite curve. The K values are averaged and treated statistically. The success of the above treatment is gratifying and provides information that is likely to be of value in future work.

TABLE II - COMPOSITE PRESSURE-TIME CURVE, THERMAL DECAY CONSTANT AND OVERSHOOT DATA

ΔP_{max} PSI	ΔT_{max} C°	K Cal/Sec.ft^{2}C°	Overshoot PSI	Per Cent Overshoot
26.0	483	2.1	1.5	5.8
24.3	451	2.3	2.1	8.6
21.9	407	2.4	1.5	6.8
21.3	396	2.2	2.8	13.1
16.0	297	2.0	4.0	25.0
15.6	290	2.6	2.2	14.1
12.2	227	3.1	1.0	8.2
10.9	202	2.5	1.8	16.5
10.3	191	2.1	1.5	14.6
8.7	162	2.5	3.0	34.5
7.5	139	3.0	2.4	32.0
		Avg. 2.4 $\pm\sigma$ 5.1		

The hump is not so amenable to explanation; however, several of its characteristics are of interest. The curves show that the apparent overshoot disappears in about 100 milliseconds. This coincides with the disappearance on the PE records of shock waves. Further, no correlation seems to exist between the magnitude of the hump and the "static" pressure level (Table II). This points to the shock wave as being primarily responsible. The hump on the records could result from the fact that the gages will give an integrated response to the many shock reflections reaching it while at the same time responding to the "static" pressure. Thus, while shocks persist the records would show pressure values higher than predicted by Eq. 6.

It is also possible that the gage overshoots in response to the successive reflected shocks. Such an overshoot would also be mainly a function of the shock pressure level. In either case the initial hump must be ignored in determining maximum "static" pressure, ΔP_{max}. The relatively flat post-shock decay (beyond 100 milliseconds) was used to extrapolate back through the hump to get ΔP_{max}.

The curves of Fig. 3 were interpreted in light of the above discussion. Table III includes the values ΔP_{max} for

TABLE III - MAXIMUM "STATIC" PRESSURE RISE (ΔP_{max}) AND HEAT VALUES (h)

Explosive Composition	AIR		Heat of Combustion cal/gm	% Diff.	NITROGEN		Heat of Detonation cal/gm	% Diff.
	ΔP_{max} PSI	Chamber Heat cal/gm			ΔP_{max} PSI	Chamber Heat cal/gm		
Pentolite 50/50	16.0	2400	2632*	-8.8	7.5	1125	1192***	-5.6
TNT (early data)	21.2	3472	3455*	+0.5	---	----	----	---
RDX/Al/Wax								
98/0/2	15.6	2340	2284**	+2.4	8.7	1305	(1203***	(+8.5
76/22/2	21.3	3195	3367**	-5.1	10.3	1545	(1235****	(+5.7
63/35/2	24.3	3645	4006**	-9.0	12.2	1830		
48/50/2	26.0	3900	4744**	-17.8	10.9	1635		
28/70/2	21.9	3285	5728**	-42.6	4.4	660		

* Measured values; reference (9)

** Derived from measured values: RDX-2120 cal/gm, Wax-10,340 cal/gm and Aluminum 7039 cal/gm for γ - Al_2O_3. This value is from heat of formation for γ - Al_2O_3(400 kcal/mole) and heat of transition of γ - Al_2O_3 to α - Al_2O_3(20.6 kcal/mole). See Wartenburg, Z. anorg. allgem. Chem. 269, 76-85 (1952); X-ray examination indicated that γ -Al_2O_3 was chief component of chamber residue.

*** Computed by D. Price (NOL). It was assumed that Wax did not react.

**** This is 98% of value measured in Woolich Calorimeter for pure, refined RDX. See ARE memo 1/51, Heat of Detonation of High Explosives (July 1951).

NOTES:

H_2O is gaseous in all values above.

Chamber heats for shots in nitrogen are all single shot values except for three replicate pentolite shots.

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each explosive in air and nitrogen, found by drawing a straight line through the curves from 100 milliseconds to 500 milliseconds and extrapolating back to zero time. This was felt to be the most reasonable method of interpretation.

The "static" pressure data in Table III and plotted in Fig. 5 as a function of aluminum content show a wide difference between charges fired in air and those fired in nitrogen. Now, if these "static" pressure values are employed in Eq. 6 (Theory and Physical Principles Section) some striking results are obtained. In order to have the value for the heat on a per gram basis we assume that H, the total heat released, is proportional to the weight of the charge W and we have

$$H = hW \tag{8}$$

where h is in calories per gram. Substituting Eq. 8 into Eq. 6 gives

$$h = \frac{\Delta PV}{W(\gamma - 1)} \tag{9}$$

In practical units where ΔP is in psi, V in cubic feet, W in grams, h in calories per gram, and $\gamma = 1.4$

$$h = 116.6 \frac{\Delta PV}{W} \tag{10}$$

For the experiments described in this report V = 72.4 cubic feet, W = 56.3 grams and

$$h = 150.0 \, \Delta P \tag{11}$$

The values of h computed with Eq. 11 using ΔP_{max} from Table III as the "static" pressure rise are listed under Chamber Heat. Next to the column for firings in air are values for heat of combustion. Next to the column for firings in Nitrogen are values for heat of detonation. These heats are values obtained by independent means and include computed values where measurements are not available. A comparison of the two columns for both air and nitrogen atmospheres shows remarkable agreement. The percentage difference was computed relative to the heats of detonation and combustion. These values are plotted in Fig. 6. The straight 45 degree line represents perfect agreement. The lines on either side represent 10 per cent deviation from perfect agreement. Except for the highest aluminum content mixtures, where incomplete combustion may be expected, the consistent and relatively close agreement between the chamber heats and heats

of detonation and combustion is striking. The value for TNT is from earlier work (reference 5). This value is more uncertain than the others because of poorer recording and methods of interpretation in that program.

While the heat energy released by the explosive is the fundamental variable from a physical standpoint and the discussion here has centered on it, Eq. 11, when transposed, predicts ΔP from known values of h. Percentage differences between measured "static" pressure and predicted values are, of course, the same as those listed in Table III for chamber heat and heat of combustion or detonation. Figure 5 indicates an optimum aluminum content with respect to "static" pressure for RDX of between 50 and 60 per cent in air and 35 per cent in nitrogen with corresponding heat releases of about 3900 cal/gm and 1830 cal/gm.

The nature of the scatter of these data from shot to shot and gage to gage is indicated in Fig. 7 which is a plot of all data points determined for one explosive composition. This scatter plot gives the spread of the data. While the total spread for this particular composition is approximately 10 per cent of the pressure level, most compositions had a greater spread and about 15 per cent is typical of all the inductance gage data.

It would appear that the theory holds for this closed chamber. Further, complete combustion apparently occurs in air for all except highly aluminized explosive mixtures. This must be true in free air as well (after shock wave formation) since the "static" pressure rise occurs very early, and it is difficult to see how the chamber walls could serve other than to simply contain the explosion energy in a fixed quantity of gas.

Chamber Resonance Measurements

The results of measurements on the low frequency oscillation (Fig. 2) found on all our records proved of considerable interest. These oscillations were treated as an acoustic resonance of the chamber space considered as a pipe closed at both ends. The amplitude of these oscillations were of the order of several pounds per square inch; therefore, there is some question as to whether they may be treated as ordinary acoustic waves. Assuming however, they follow regular acoustic relationships, the temperature rise of the gas due to the explosion should change the velocity of sound in the ambient gas and result in a change with temperature of the resonance frequency

of the chamber cavity. Since pressure is proportional to the temperature with no change in density, the pressure could be determined from measurement of this frequency. The equation for velocity of sound, c, in gas is

$$c = \sqrt{\frac{\gamma P_a}{\rho}} ; \qquad (12)$$

where P_a is the absolute pressure, γ is the ratio of specific heats, and ρ the density of the gas. For a closed tube of length L, the fundamental resonance frequency is

$$\tau = \frac{2L}{c} . \qquad (13)$$

If we substitute Eq. 12 into Eq. 13 and solve for the pressure,

$$P_a = \frac{4\rho L^2}{\gamma \tau^2} . \qquad (14)$$

P_a may be calculated by measuring τ, since ρ, L, and γ are known. Most of the inductance gage records produced data and some data were obtained from the PE records. τ was determined by measuring the time for approximately 20 complete cycles. Cycles were counted starting approximately 50 milliseconds after the start of the record. The period, so determined, gave an average which helped reduce the error in choosing the start and finish of a cycle. Since the pressure was decaying at the rate of 4.5 per cent per 100 milliseconds of time, any particular value for the period, which was an average of a number of cycles, gave a value of pressure at the mid-point in time between the first and last cycle of the measurement. The pressures obtained, therefore, were extrapolated from this midpoint back to zero time using 4.5 per cent decay per 100 milliseconds.

All the data are listed in Table IV. For comparison, the last column is the "static" pressure, ΔP_{max}, as directly determined with pressure gages (Table III). The values compared with the directly measured data show good agreement. Several facts stand out. While the scatter for each mixture is rather small, all average resonance values fall lower than the direct gage values. Also, it is characteristic that for low pressures - below 10 psi - the oscillation amplitudes are much reduced and difficult to read; thus the scatter for this data was higher. The technique, however, should be susceptible to great improvement over the present arrangements which produced this data only incidentally. The value of this method is that it provides at the very least a calibration free system requiring

TABLE IV - TABULATION OF PRESSURES AS DETERMINED BY CHAMBER RESONANCE METHOD
(All Pressures Given in psi)

Series / Explosive	Inductance Gage #1			Inductance Gage #2			Ind. Gage	Piezoelectric Gage			PE Gage	All Resonance Data	ΔP_{max} from Table II
	1	2	3	1	2	3	Avg.	1	2	3	Avg.	Avg.	
						FIRED IN AIR							
Pentolite	15.9	14.4	15.1	15.4	15.0	14.8	15.1	15.2	14.7	13.9	14.6	14.9	16.0
RDX/Al/Wax 98/0/2	13.2	14.3	---	13.3	14.6	13.0	13.7	12.6	13.7	---	13.2	13.5	15.6
76/22/2	22.0	---	---	22.4	---	18.0	20.8	21.1	---	20.5	20.8	20.8	21.3
63/35/2	23.3	22.1	20.1	23.1	23.6	20.3	22.1	22.3	---	21.7	22.0	22.1	24.3
48/50/2	25.8	22.5	24.0	25.6	23.8	24.4	24.4	25.2	25.9	24.8	25.3	24.7	26.0
28/70/2	20.8	20.5	18.2	20.8	19.9	18.9	19.8	23.2	20.4	----	21.8	20.3	21.8
Series 4						FIRED IN NITROGEN							
Pentolite	6.7	5.3	---	5.6	6.3	---	6.0	---	6.0	---	---	6.0	7.5
RDX/Al/Wax 98/0/2	7.4	---	---	7.1	---	---	7.2	6.0	---	---	---	6.8	8.7
76/22/2	7.7	---	---	7.8	---	---	7.8	8.4	---	---	---	8.0	10.3
63/35/2	---	---	---	---	---	---	---	---	---	---	---	---	12.2
48/50/2	9.1	---	---	8.8	---	---	9.0	9.2	---	---	---	9.0	10.8
28/70/2	3.8	---	---	3.8	---	---	3.8	2.2	---	---	---	3.3	4.4

only the crudest of gage systems for quick relative measurements of pressure. If the accuracy of Eq. 14 can be established, or a more accurate equation found, then this method will have all the virtues described above and in addition will produce absolute values.

Shock Wave Measurements

The peak pressure of the incident shock was measured on the high speed PE records. These records showed an apparent base-line shift after the start of the record; however, one channel was felt to have recorded satisfactorily the incident shock. The data were collected from these records. Peak pressure in the incident shock (Table V) are in reasonable agreement with free air shock data for 3-lb charges (starred data) at a reduced distance $\lambda = 6.00$ ft/lb$^{1/3}$.

Worthy of note is the consistently low values for the nitrogen shots compared with free air values indicating an after-burning contribution to the shock when fired in air. An after-burning contribution to the shock wave is frequently mentioned in the literature (reference 12), and some attempts at measurement have been made using gas filled balloons about a charge (reference 1). The closed chamber provides an ideal means for measurement of this effect. The few shots of this program in nitrogen, however, preclude any quantitatively significant results.

Solid Explosion Products

On all shots except non-aluminized explosives in air a solid residue was left on the bottom and sides of the chamber. In air the low percentage aluminum mixtures left a fine light grey powder. In mixtures of higher percentage aluminum, residues were increasingly fluffy in texture. Air movement would cause the material to snowball down the sides. Preliminary X-ray analysis of these residues was performed to determine the metallic aluminum content. Only in the 70% mixture was any found. About nine per cent of the residue by weight consisted of aluminum. In nitrogen the aluminized explosives behaved similarly, but the residues were black, due apparently to residual carbon. Quantitative data were not obtained, but aluminum nitride was found in two residues. These results and more detailed chemical analyses are treated in reference 14. The pure explosives in nitrogen left a carbon residue; RDX left a light dusting of carbon; pentolite left much more carbon.

TABLE V - PEAK PRESSURE IN INCIDENT SHOCK WAVE AT λ = 6.00 ($ft/lb^{1/3}$)

Composition	Air Data						Nitrogen Data	
RDX/Al/Wax	String 1	String 2	String 3	Avg.	With 15% Transit Time Correction	Free Air Values	Avg.	With 15% Transit Time Correction
98/0/2	20.4	17.1	20.9	19.5	22.4	24.0*	17.8	20.5
76/22/2	25.5	18.0	21.5	21.7	25.0	27.7*	20.8	23.9
63/35/2	25.3	21.3	19.2	21.9	25.2	25.5*	18.5	21.3
48/50/2	---	18.6	17.5	18.0	20.7	---	14.0	16.1
28/70/2	10.0	11.0	10.9	10.6	12.2	---	7.3	8.4
TNT/PETN 50/50	---	19.0	17.1	18.0	20.7	24.6**	17.8	20.5

* Reference 10
** Reference 11

COMMENTS ON SOME CONSEQUENCES AND POSSIBLE APPLICATIONS OF THIS WORK

This section discusses a number of military and non-military implications of the theory and experimental results described in this report.

"Static" Pressure Scaling Law for Charge Weight and Chamber Volume

For the purposes of this discussion we solve Eq. 9 for ΔP. Thus,

$$\Delta P = (\gamma - 1) \frac{hW}{V} \qquad (15)$$

Equation 15 suggests that the "static" pressure may be predicted for any explosive (variable h) in any quantity (variable W) detonated in any size enclosure (variable V), provided it is large enough that the explosion product gases are insignificant in amount compared with the initial ambient gas. The proportionality of ΔP to h was shown by UERL and NOL measurements over a wide range of values. While UERL data were obtained for several weights of charge and in a chamber much larger in volume than that at NOL, the experimental arrangements at UERL were such as to prevent use of their data for a check of volume and weight scaling. Some verification will be undertaken at NOL in the future, although present facilities are limited for this purpose.

Relative Importance of "Static" and Shock Wave Pressure

With "static" pressure quantitatively defined, its role and importance compared to the shock wave in causing damage may be examined. The "static" pressure is a uniform pressure throughout the enclosure and independent of the location of the charge when detonated; while the shock wave pressure is a rapidly varying function of distance between charge and target surface. Thus a charge immediately adjacent to a target surface may tear a hole in it due to shock pressure. This would result in a reduction in the importance of the role of "static" pressure. On the other hand a charge located centrally in a target enclosure will provide a relatively full "static" pressure effect on all target surfaces while shock wave effects are sharply reduced.

The free air pressure-reduced distance curves for the shock wave of a typical explosive is plotted in Fig. 8. Superimposed on this plot is the curve for the "static" pressure versus reduced distance developed in spherical chambers with radii corresponding to the shock reduced distance, λ, for the same explosive.

The meaning of reduced distance for the "static" pressure may be shown from Eq. 15,

$$\Delta P = (\gamma - 1)\frac{hW}{V}.$$

Let $V = 4/3\,\pi r^3$, where r is the radial distance from a charge, and V is the volume of a sphere with that radius. Then

$$\Delta P = \frac{(\gamma - 1)hW}{4/3\,\pi r^3}. \qquad (16)$$

For any particular explosive and ambient gas

$$\Delta P = \frac{k}{r^3/W} = \frac{k}{\lambda^3}, \qquad (17)$$

where $\lambda = \frac{r}{W^{1/3}}$ and $k = \frac{(\gamma - 1)h}{4/3\,\pi}$.

The straight line on Fig. 8 is a plot of ΔP vs λ. For any particular λ the plot gives incident shock pressure at the wall of a spherical chamber of λ radius. The "static" pressure developed in such a size chamber for the same weight of charge that produced the shock is given by the "static" pressure plot. The plot shows the order of magnitude of the "static" pressure compared to that of the incident shock pressure at the wall of the spherical chamber over a large range of target sizes. This graph applies for any weight of charge.

Different explosives and different gases shift these lines. The shock pressure will vary as much as 25 per cent either way. The "static" pressure will vary about 500 per cent altogether as the heats realized per gram of explosive vary from 1000 calories to 5000 calories.

However, the plot does not indicate the chronology of the two phenomena. While the shock lasts for a few milliseconds for charges weighing 1 lb. or less, the "static" pressure rises within a few milliseconds following the arrival of the incident shock and stays at that pressure until target rupture, gas leaks, or thermal conduction dissipates the pressure. Durations on the order of hundreds of milliseconds are characteristic of the "static" pressure.

Carefully designed experiments with destructible enclosures, based on the above, may be performed to provide more complete information on the relative role of shock and "static" pressures in doing damage.

Altitude Effects

Aircraft targets are of primary interest for blast in a closed space; therefore, the effect of altitude on the "static" pressure is of interest. Variations in density, temperature and oxygen content of the atmosphere with altitude must be considered.

Assuming the gas law holds at any altitude, Eq. 15 will hold. Pressure at any altitude is related to the density and temperature at that altitude by the gas law and the gas constant. Thus Eq. 15 gives the same rise in pressure regardless of ambient P, T, and ρ.

The effect of reduced oxygen concentration is not as clear. At sea level the several high explosives measured in this work used the oxygen of the atmosphere and heat of combustion was realized even though the explosives were oxygen deficient. In the limiting case of extreme altitude and essentially no oxygen one would expect results similar to those reported here for nitrogen. That is to say, only the heat of detonation would be realized with a consequent reduction in "static" pressure by as much as two-thirds depending on the explosive. Thus, if the interior space of an airplane were at external ambient conditions one would expect from a given weight of explosive less damage at high than at low altitudes to result from "static" pressure phenomena. In general, an airplane should be less subject to damage due to "static" pressure phenomena if its interior spaces are free of oxygen.

Considerations for an Optimum Explosive

The nature of the "static" pressure phenomena sets different requirements on the characteristics of explosives for optimum performance as compared with the characteristics desirable for optimum shock wave performance. The theory indicates that if the explosive will be employed in an atmosphere of air at sea level, an explosive with the maximum heat of combustion is called for; if the ambient conditions will be oxygen free, maximum heat of detonation is desired.

For single component explosives, heats of combustion vary from 1500 to 3500 cal/gm; heats of detonation from 1000 to 1500 cal/gm. It is characteristic of single component explosives that the higher the heat of detonation the lower the heat of combustion. However, when aluminum is added to most explosives both heat of detonation and heat of combustion go up. In this program optimums were found for RDX-Al mixtures in air in the vicinity of 50 per cent aluminum, 3900 cal/gm; in nitrogen, 35 per cent aluminum, 1830 cal/gm. This would indicate that an RDX-Al mixture containing between 35 and 50 per cent aluminum would be superior to any known pure explosive in either normal or oxygen free air (high altitudes), so far as "static" pressure is concerned.

The optimum aluminum content for other explosives is not known at present.

Explosion Calorimetry and Fragment Velocity Using "Static" Pressure Technique

The apparatus of these experiments suggests itself as a novel technique for determining certain properties of explosives heretofore obtained only with considerable difficulty and uncertainty. Very few attempts have been made to measure heat of detonation. Generally a few grams of explosive under confinement are used in an adapted bomb calorimeter. It is not certain that the heat realized in such a situation is the same as that from the detonation of a full sized charge. "Static" pressure measurement in an inert atmosphere using a substantial quantity of explosive as in the present nitrogen experiments appears to be a sound approach to the measurement of this quantity.

Another interesting possible application is the measurement of the velocity of fragments from metal cases around explosives. The "static" pressure method would involve firing a charge with and without a case. The "static" pressure would be different in the two instances. The difference in the thermal energies computed from the "static" pressure would be the kinetic energy of the fragments. Knowing the mass of the case and its kinetic energy, the mean velocity of the fragments could be computed. This technique assumes that negligible fragment energy is lost to the air by friction and that the kinetic energy of the fragments is transferred to the stopping medium and not transferred back to the gas. The effect of any post detonation reaction (after burning) on the fragment velocity could also be isolated by using an inert ambient gas.

CONCLUSIONS

Explosives in completely closed spaces develop a "static" uniform pressure a few milliseconds after the initial shock wave which persists for times on the order of seconds. This pressure

is due to heating of the gas in the chamber by the energy released in the explosion. Pressures measured in the NOL chamber were found to agree with values predicted by the equation

$$\Delta P = (\gamma - 1)\frac{hW}{V} \qquad (20)$$

which is derived from the mass heating and ideal gas laws. The theory assumes the enclosed volume is large compared to that of the charge.

The above equation predicts the "static" pressure if an explosion takes place in a closed space containing air at sea level, provided the heat of combustion of the explosive is used for h. If the heat of detonation is used for h, a "static" pressure rise is obtained close to measured values for RDX and pentolite when fired in an oxygen free atmosphere.

For two explosives, RDX (single shot) and pentolite (3 shots), fired in N_2, the heat computed from the above equation was within 10 per cent of the computed heat of detonation. These preliminary results are promising and indicate the desirability of further measurements on heats of detonation for various explosives.

The "static" pressure optimum aluminum content for RDX-aluminum mixtures was found to be 50 to 60 per cent in air and 35 per cent in nitrogen.

Measurement of the acoustic resonance frequency of the chamber cavity is a promising method for determining "static" pressure independent of gage calibration.

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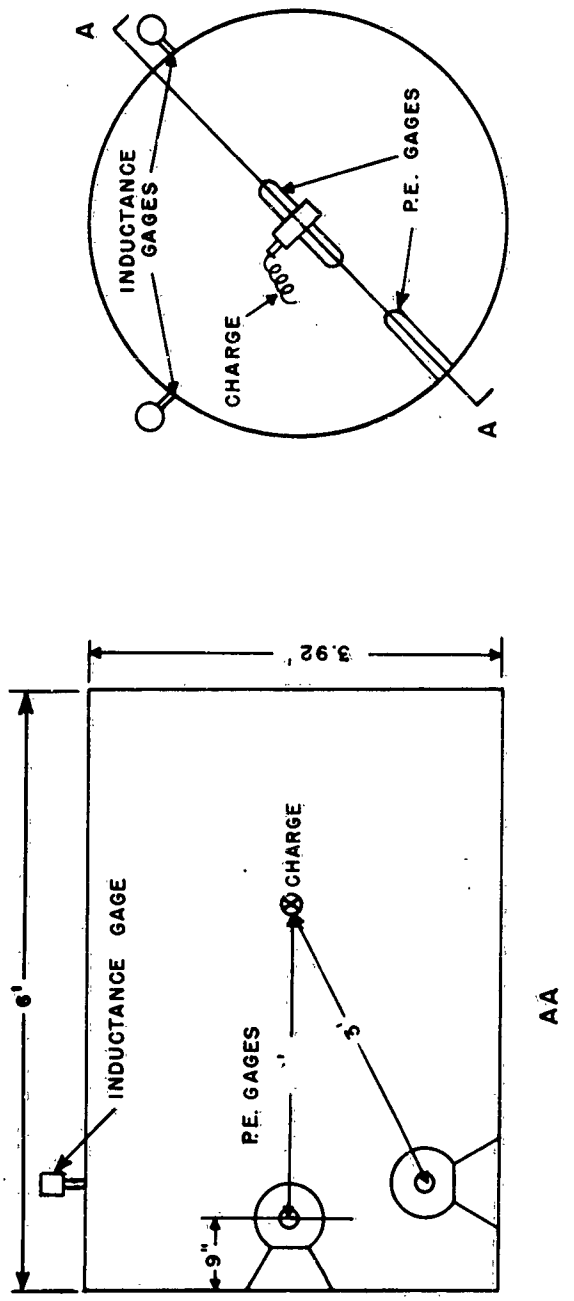
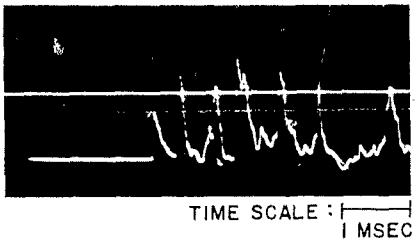
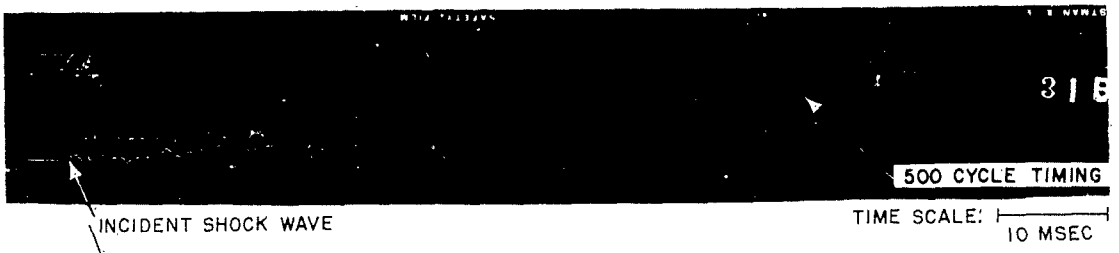


FIG. 1 GAGE - CHARGE ARRANGEMENT

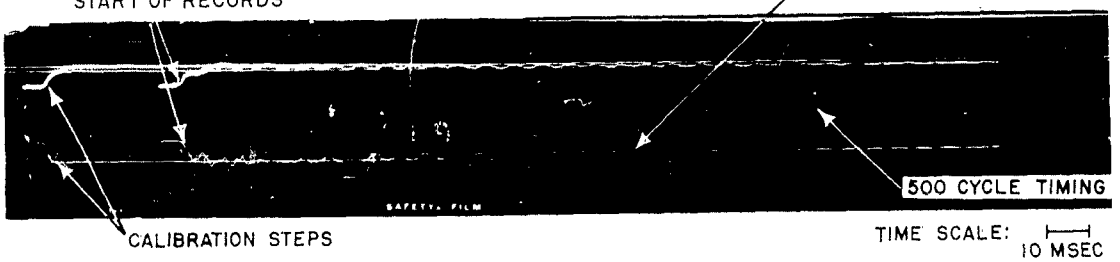


2a INCIDENT SHOCK AND REFLECTIONS
(3X ENLARGEMENT OF FIG.2b)



2b P.E. GAGE-HIGH SPEED

2c P.E. GAGE-LOW SPEED



2d INDUCTANCE GAGE RECORD-LOW SPEED

FIG. 2 TYPICAL RECORDS - SHOT 19

MIXTURE %			SYMBOL
RDX	Al	WAX	*
98	0	2	◒ ◓
76	22	2	□ ■
63	35	2	△ ▲
48	50	2	○ ●
28	70	2	◔ ◕
PETN	TNT		
50	50		◇ ◆

* NOTE: FILLED SYMBOLS INDICATE SECOND READING (SEE TEXT)

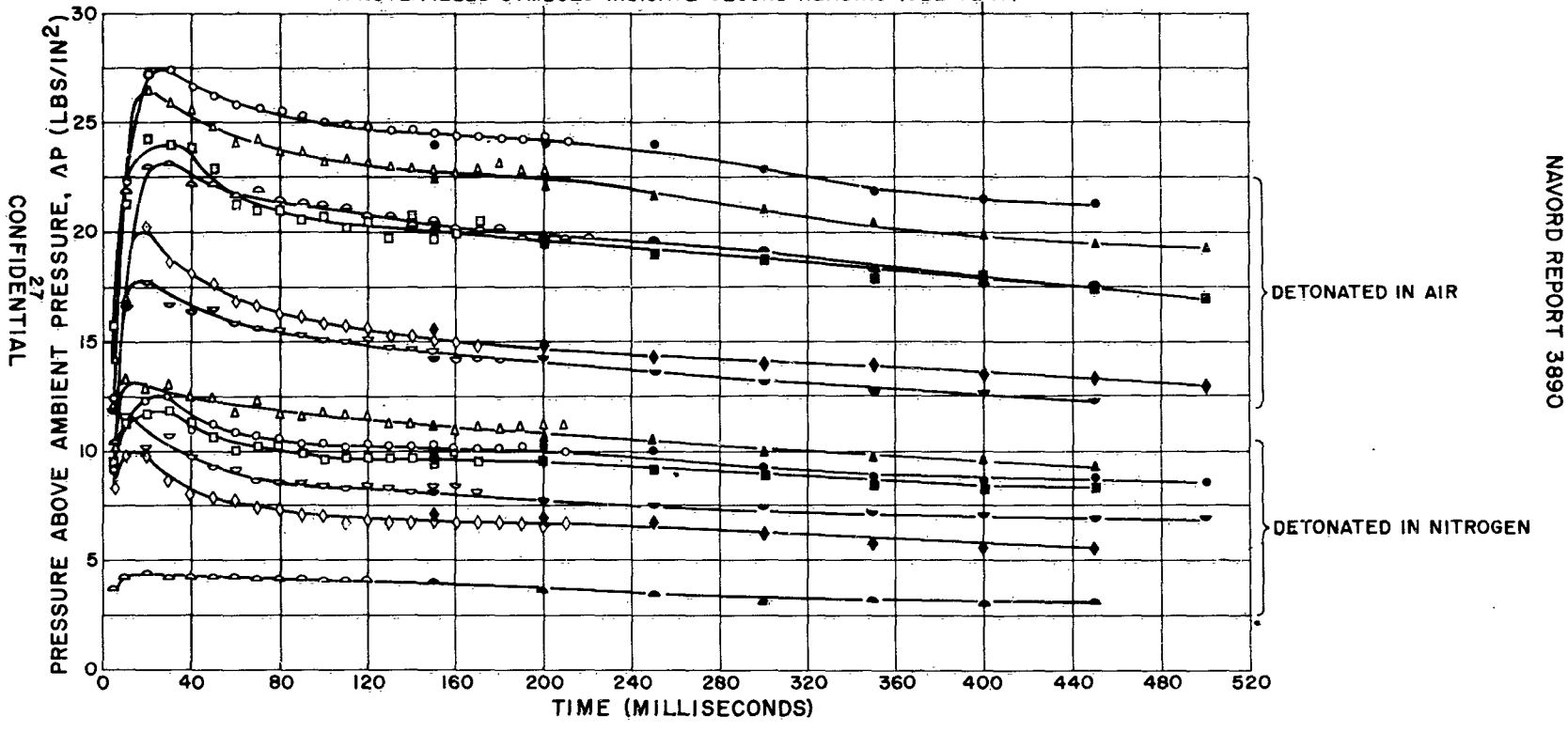


FIG. 3 COMPOSITE PRESSURE-TIME HISTORIES OF "STATIC" PRESSURE FOR SIX EXPLOSIVES DETONATED IN AIR AND NITROGEN

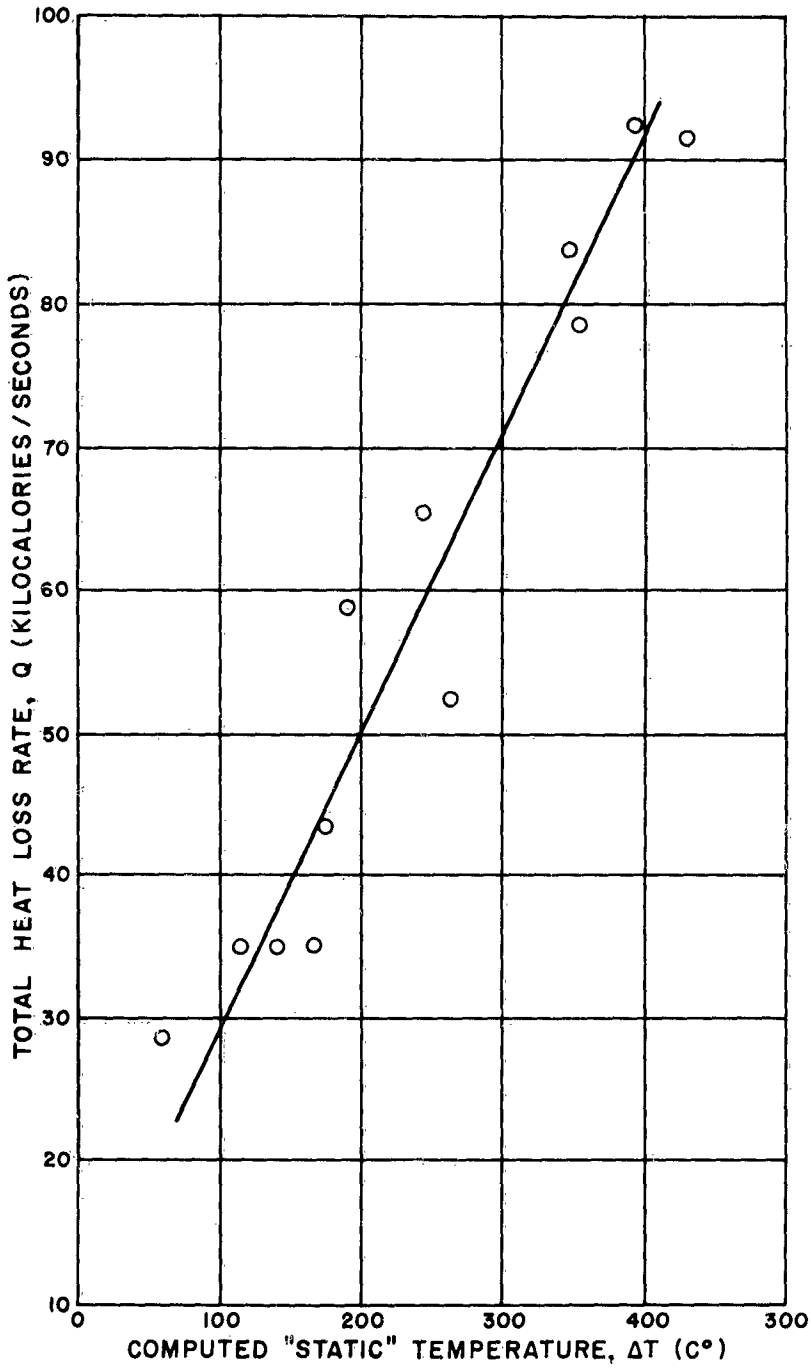


FIG. 4 TOTAL HEAT LOSS RATE
VS "STATIC" TEMPERATURE

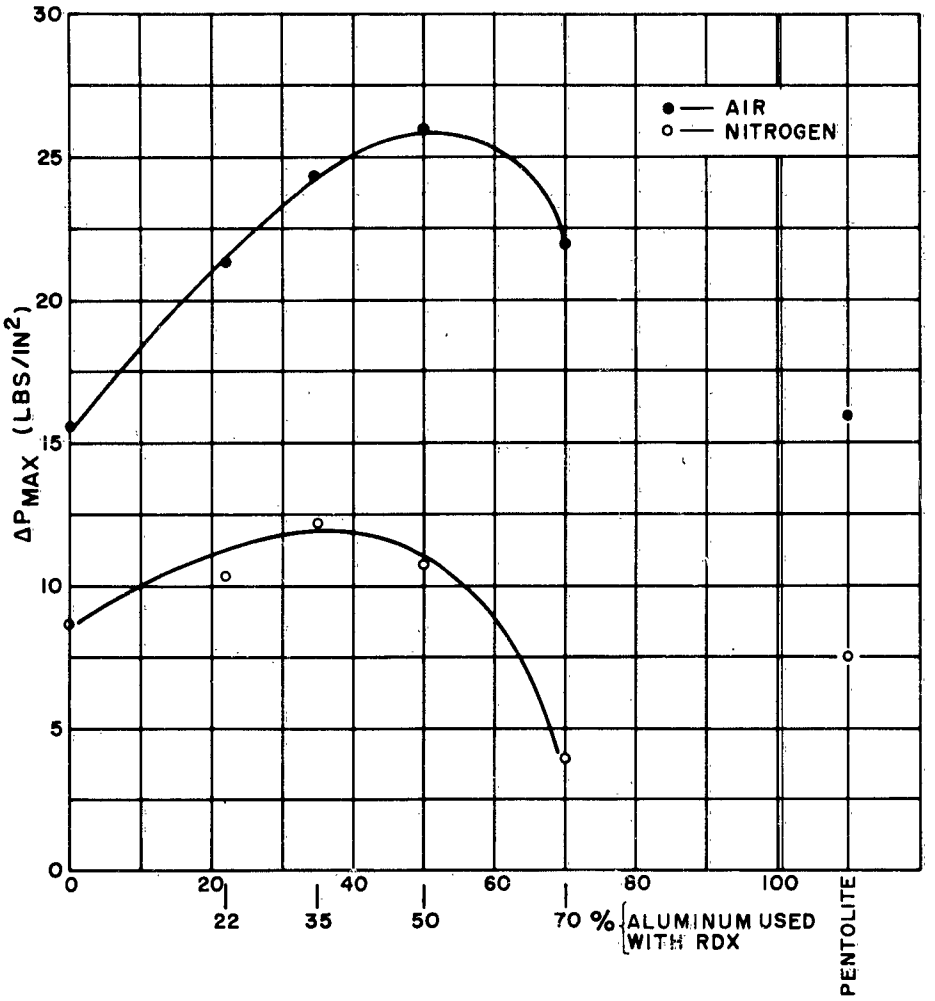


FIG. 5 ΔP_{MAX} IN AIR AND NITROGEN VS EXPLOSIVE COMPOSITION

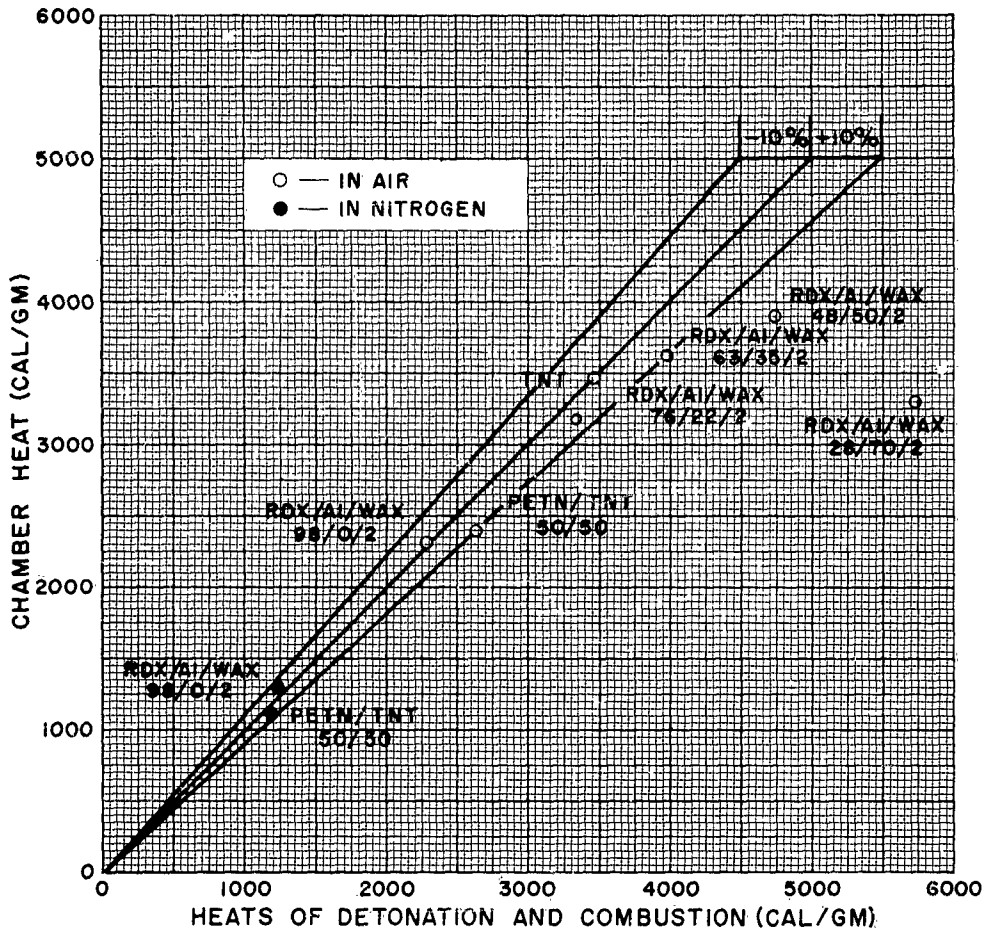


FIG.6 CHAMBER HEATS VS HEATS OF DETONATION AND COMBUSTION

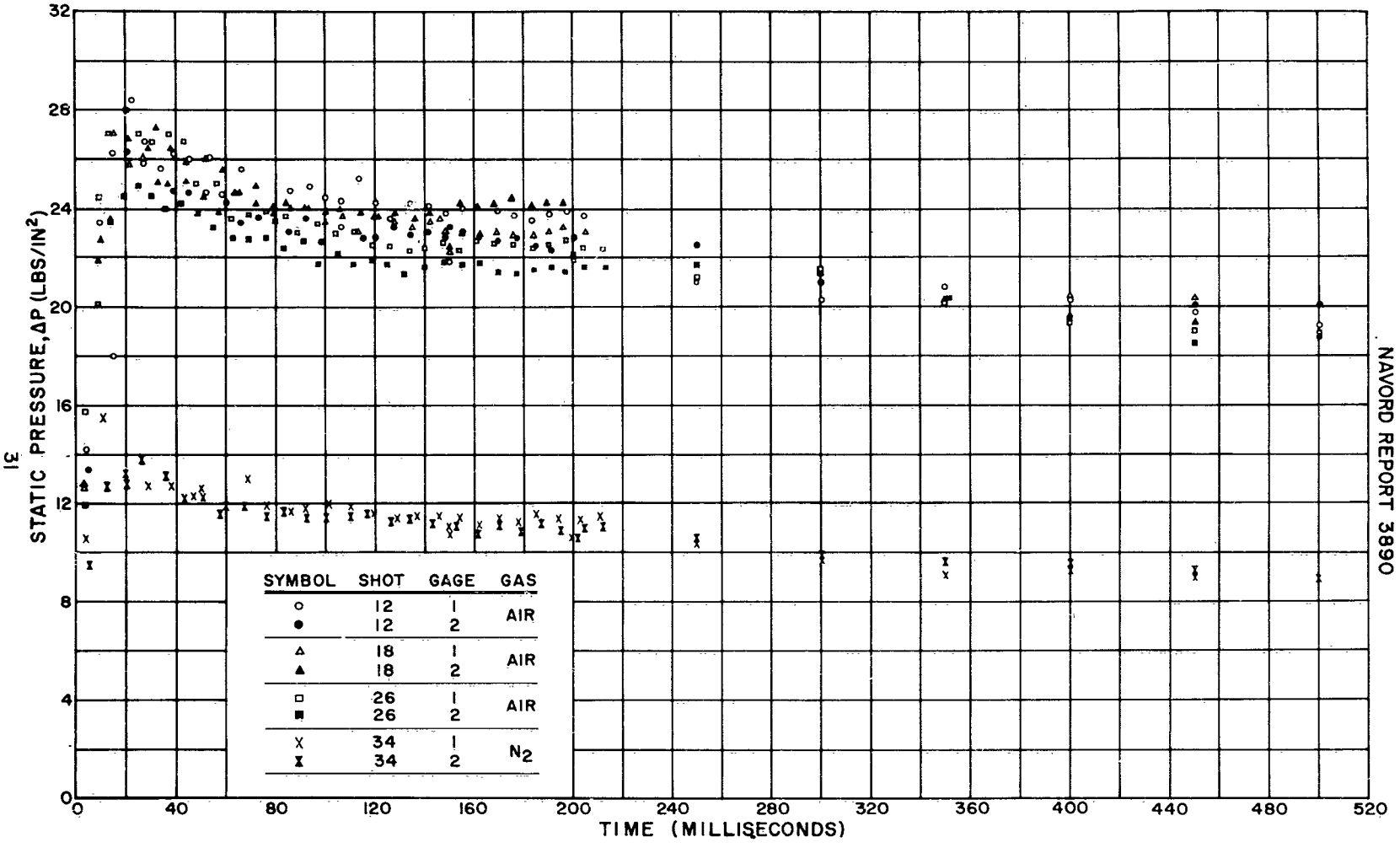


FIG. 7 PRESSURE-TIME SCATTER PLOT FOR ONE EXPLOSIVE
RDX/AI/WAX 63/35/2, 3 SHOTS IN AIR, ONE SHOT IN NITROGEN, TWO GAGES ON EACH SHOT

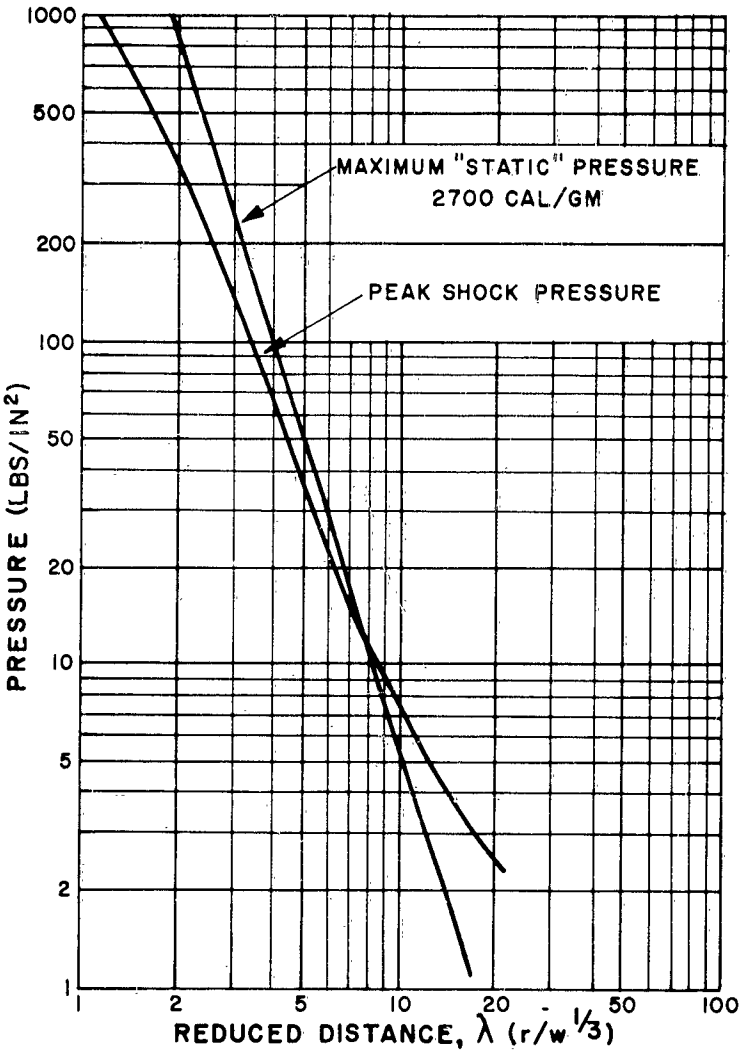


FIG. 8 SHOCK PRESSURE AND EQUIVALENT SPHERE "STATIC" PRESSURE VS REDUCED DISTANCE (λ) FOR PENTOLITE

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